Four-wave-mixing based optical wavelength converter device

DESCRIPTION

The present invention relates to a wavelength converter device comprising a structure having a plurality of cascaded optical resonators.

The present invention relates, moreover, to an use of a structure comprising a plurality of cascaded optical resonators for generating a radiation at frequency ω_g through non-linear interaction between at least one pump radiation at frequency ω_p and at least one signal radiation at frequency ω_s.

Furthermore, the present invention relates to an use of a structure, comprising a plurality of cascaded optical resonators made of a non-linear material, for altering the optical spectrum of at least one signal radiation at frequency ω_s by non-linear interaction within the material of the optical resonators.

Moreover, the present invention relates to an apparatus for an optical network node comprising a routing element and a wavelength converter device of the invention.

Additionally, the present invention relates to an optical communication line comprising an optical transmission path for transmitting at least one signal radiation at frequency ω_s and a wavelength converter device of the invention.

Structures made of a plurality of cascaded optical resonators are known.

For example, A. Melloni et al. ("*Synthesis of direct-coupled-resonators bandpass filters for WDM systems*", Journal of Lightwave Technology, Vol. 20, No. 2, February 2002, pages 296-303) disclose a structure consisting of cascaded direct-coupled ring resonators or cascaded Fabry-

Pérot resonators for use as a bandpass filter.

Furthermore, US 5 311 605 discloses an optical device comprising a length of optical waveguide having incorporated therein an extended sequence of coupled single-resonator structures for use as an optical slow wave structure. This document states that the structure may also be designed to provide a desired filter characteristic, a dispersion such as to correct for undesirable dispersion in other components of an optical system or to provide pulse expansion or compression. The Applicant notes that no mention of use of non-linear interactions is made in this document.

In a WDM (wavelength division multiplexing) optical communication system/network, wavelength management and wavelength routing control between nodes of the system is crucial for preventing wavelength blocking and facilitating cross connecting. To this end wavelength converter devices able to shift a signal radiation from an optical channel to another are required.

Non-linear wavelength converter devices using a parametric process are known.

A parametric process is a process typical of materials having a non-linearity of the χ_2 or χ_3 type according to which electromagnetic radiation at predetermined frequencies that propagate in such materials interact with each other for generating electromagnetic radiation at different frequencies from those that have generated them.

For example, a parametric process is a process according to which a pump radiation at frequency ω_p that propagates in a non-linear material, interacting with a signal radiation at frequency ω_s, generates a radiation at frequency ω_g.

Typical parametric processes are a difference frequency generation process, according to which $\omega_g = \omega_p - \omega_s$, a sum frequency generation process, according to which $\omega_g = \omega_p + \omega_s$,

a second or third harmonic generation process, according to which $\omega_g = 2\omega_p$ or, respectively, $\omega_g = 3\omega_p$ and a degenerate four-wave mixing (FWM) process according to which $\omega_g = 2\omega_p - \omega_s$ or $\omega_g = 2\omega_p + \omega_s$.

5   For example, one-dimensional-photonic-crystal multiresonator structures (also called photonic band-gap structures) have been proposed for wavelength conversion through a second harmonic generation parametric process.

A one-dimensional photonic crystal structure typically
10 consists of a periodical alternation of two layers of material having different refractive indexes. The multiple reflections at the interfaces between the two layers at different refractive index generate constructive and destructive interference between the transmitted light and
15 the reflected light, so that the propagation of electromagnetic waves in the photonic crystal structure is allowed in some intervals of frequencies (or wavelengths) and forbidden in other intervals. The layers typically have thicknesses a and b of $\lambda/4n$ (quarter-wave layer) or $\lambda/2n$
20 (half-wave layer), where λ is the operating wavelength and n the refractive index of the layer, so as to form a periodic quarter-wave, half-wave or mixed quarter-half-wave structure.

WO 99/52015 describes a second harmonic generator based on
25 a periodic photonic crystal structure. The described structure comprises a plurality of layers of a first and a second material that periodically alternate, and has a band edge at the pump radiation frequency and a second transmission resonance near the band edge of the second
30 order band gap at the generated second harmonic frequency. The layers have thicknesses a and b of $\lambda/4n$ or $\lambda/2n$.

US 6 002 522 discloses a structure having materials with different refractive indexes and periodically arranged to form a photonic band-gap structure. Furthermore, it
35 discloses to set the period of two different materials

having different refractive indexes (that is the thickness of a pair of two different materials) at nearly half the wavelength of light used. This document teaches that the structure can be used to manufacture a wavelength converter
by second harmonic generation, if a second-order non-linear optical material is used, and an optical switch if a third-order non-linear optical material is used.

Wavelength converter devices using the four-wave mixing process are known.

EP 0 981 189 discloses a non-linear wavelength converter device comprising an optical waveguide doped with a rare earth element. An input optical signal and at least one pump light cause four wave mixing (FWM) to occur in the optical waveguide and the FWM causes a converted optical
signal to be produced in the optical waveguide. The optical signal and the pump light are amplified in the optical waveguide thereby the four-wave mixing converted optical power is increased.

In order to increase the four-wave mixing converted optical
power, also wavelength converter devices using the four-wave mixing process in a single optical resonator have been disclosed.

P.P. Absil et al. ("*Wavelength conversion in GaAs micro-ring resonators*", Optics Letters, Vol. 25, No. 8, April 15,
2000, pages 554-556) disclose a device comprising a single micro-ring resonator wherein a pump wave of frequency ω_p and a signal wave of frequency ω_s are launched into the ring at two different resonant frequencies. A new converted wave is generated by degenerate FWM at the frequency $\omega_g = 2\omega_p - \omega_s$. The Authors states that non-linear interactions are
enhanced in the resonator.

US 5 243 610 disclose a device comprising an input for an input light signal, an optical source for generating a pump light signal, a non-linear optical medium for receiving the

pump and input light signals and an output. The non-linear optical medium includes a Fabry-Perot type semiconductor laser and frequency converts the input light signal to generate an output light signal using non-degenerate four-
5   wave mixing. In this document it is stated that the FWM may be generated at a relatively lower power due to an internal electric field enlarged by confining the pump light and input signal light into a resonator.

US 5 550 671 discloses a device comprising an input for a
10 signal radiation, an optical source for generating a pump radiation, a laser cavity and an output. The laser cavity is composed of a rare-earth doped fiber and is defined by a pair of fiber Bragg gratings. By propagating through the laser cavity the signal and pump radiation generate by four wave mixing a new converted signal of wavelength within 10%
15 of the signal radiation wavelength. In this document it is stated that the device can be made in compact form with a cavity length as small as 100m and can provide inverted signals at the same intensity as the input signals.

20 The Applicant notes that in the above mentioned devices with a single optical resonator, the four-wave mixing converted optical power (i.e. the optical power of the radiation generated by four-wave mixing) depends on the pump power, on the resonator physical length and on the
25 power reflectivity of the reflectors forming the resonator.

For cost, availability and reliability reasons, the pump power should be kept as low as possible. Therefore, the resonator physical length and the power reflectivity should be kept as high as possible in order to achieve high
30 converted optical power values.

However, in this regard the Applicant notes that also the frequency difference between two consecutive resonant frequencies (free spectral range or FSR) and the bandwidth B of an optical resonator depend on the physical length and
35 on the power reflectivity. Furthermore, for use in a WDM

optical communication system, the FSR and bandwidth B of the resonator should be set according to the WDM system requirements (e.g., the bandwidth B' of the WDM optical signals and the wavelength spacing thereof which is
5   typically selected according to ITU-T recommendations).

It follows that, the physical length and the power reflectivity of the optical resonator should be selected according to the WDM optical communication system requirements and cannot be freely set to any desired value.

10 Accordingly, the Applicant notes that external factors may not allow desired values of the FWM converted optical power to be achieved. Thus, the above mentioned devices, using the four-wave mixing process in a single optical resonator, are not versatile.

15 The Applicant has thus faced the technical problem of providing an efficient and versatile wavelength converter device, capable of achieving high converted optical power values and, at the same time, meeting WDM optical communication system requirements.

20 It is a first aspect of the present invention a wavelength converter device, for generating a converted radiation at frequency ω_g by interaction between at least one pump radiation at frequency ω_p and at least one signal radiation at frequency ω_s, comprising
25 * an input for said at least one signal radiation at frequency ω_s;
    * a pump light source for generating said at least one pump radiation at frequency ω_p;
    * an output for taking out said converted radiation at
30   frequency ω_g;
    * a structure for transmitting said signal and pump radiation, said structure including one optical resonator comprising a non-linear material, having an optical length of at least $40*\lambda/2$, wherein λ is the wavelength of
35   the pump radiation, and resonating at the pump, signal

and converted frequencies ω_p, ω_s and ω_g,
characterized in that said structure comprises a further
optical resonator coupled in series to said optical
resonator, said further optical resonator comprising a non-
5   linear material, having an optical length of at least
$40*\lambda/2$, wherein λ is the wavelength of the pump radiation,
and resonating at the pump, signal and converted
frequencies ω_p, ω_s and ω_g; wherein by propagating through
said structure the pump and signal radiation generate said
10   converted radiation by non-linear interaction within said
optical resonators.

As disclosed in more detail hereinafter, in the device of
the invention the converted optical power depends on the
resonator optical length, the resonator power reflectivity
15   and the number of cascaded optical resonators. Therefore,
even if the resonator optical length and the resonator
power reflectivity are constrained by external factors, the
desired converted optical power value can still be achieved
by suitably selecting the number of cascaded optical
20   resonators.

Thus, the device of the invention can be suitably designed
both to achieve high converted optical power values and to
meet WDM optical communication system requirements.

In the present description and claims, the expression
25   "resonator" is used for indicating a device with a bounded
path of such dimension that a standing electromagnetic wave
can be sustained by application of energy of appropriate
frequency. Typical examples of an optical resonator are a
guiding medium (conventionally named "resonant cavity" or
30   "cavity") bounded by two cascaded partially reflecting
mirrors or a closed-ring optical waveguide (conventionally
named "microring") with a coupling portion to allow the
electromagnetic radiation to enter and exit from the ring.
The optical resonator has a comb of resonant frequencies
35   that are substantially equispaced in frequency. The
distance between two adjacent resonant frequencies is named

free spectral range (FSR). The FSR depends on the group length L_g of the resonator (FSR = c/L_g). L_g is defined as L_g = $c*\tau_g$, wherein c is the speed of light and τ_g is the group delay of the resonator which depends on the type of the

5   resonator and on the material. In the case of a guiding medium bounded by two cascaded partial reflectors, non-dispersive medium and concentrated reflectors, L_g is twice the optical distance between the two reflectors. In the case of distributed reflectors L_g can be numerically

10   calculated by techniques well known in the art as, for example, by means of the "coupled mode theory" (see for example S. Legoubin et al., "*Free spectral range variations of grating-based Fabry-Perot filters photowritten in optical fibers*", J. Optical Society of America, August

15   1995, Vol. 12, No. 8, pages 1687-1694). Lastly, in the case of a closed-ring optical waveguide in a non-dispersive medium L_g is the optical length of the ring.

Moreover, in the present description and claims, the expression

20   - "optical length" for a radiation propagating in a propagation medium is used for indicating the product between the refractive index of the medium and the physical length thereof;

- "four wave mixing efficiency" is used for indicating the
25   ratio $P_c/(P_p^2*P_s)$, where P_c is the converted radiation optical power, P_p the pump radiation optical power and P_s the signal radiation optical power;

- "bandwidth" B for an optical resonator is used for indicating the full width at half maximum (FWHM) of each
30   resonance;

- "power reflectivity" or "reflectivity" is used for indicating either the ratio between the power of the radiation reflected by a partially reflecting mirror of a resonant cavity and the power of the incident radiation,

or the ratio between the power of the radiation not coupled outside by the coupling portion and the power of the incident radiation in a closed-ring optical waveguide resonator;

5   - "reflector" is used for indicating an element adapted to form a resonator as, for example, a mirror of a resonant cavity, a coupling portion of a closed-ring optical waveguide resonator or a defect in a photonic crystal waveguide cavity;

10   - "partial reflector" is used for indicating a reflector having a power reflectivity lower than 100%;

- "multiresonator structure" is used for indicating a structure comprising a plurality of cascaded optical resonators;

15   - "multistage device" is used for indicating a device comprising a plurality of cascaded structures with phase-mismatch compensating elements interposed between one structure and the other;

- "non-linear material" is used for indicating a material
20   having at least one of the χ_2, χ_3 susceptibility coefficients greater than zero.

Furthermore, in a WDM optical communication system, the signal radiation having different wavelengths are each assigned a specific band of wavelengths having
25   predetermined width - hereinafter called "channel". Each of said channels is characterised by a central wavelength value and by a range of wavelength, centred about said central wavelength, which is defined "signal bandwidth or band" B'.

30   The dependent claims set out particular embodiments of the invention.

The non-linear material of the optical resonators can be of

the χ_2 type. Advantageously, it is of the χ_3 type. In this latter case, the converted radiation is preferably generated by four-wave-mixing. In a preferred embodiment of the invention, the four-wave-mixing is of the degenerate
5   type.

In a preferred embodiment of the invention, the pump radiation frequency ω_p and the signal radiation frequency ω_s are different.

Advantageously, the optical resonator and the further
10 optical resonator are directly connected in series.

Advantageously, the optical resonator and the further optical resonator are made of the same material. This facilitates the manufacturing process of the structure.

Advantageously the optical resonator and the further
15 optical resonator are made of a transparent material at the working wavelengths (or frequencies) of the device.

For example, the working wavelengths are selected within the interval comprised between 0.7 µm and 1.9 µm. According to a variant, they are selected within the interval
20 comprised between 0.7 µm and 1.8 µm. Preferably, the working wavelengths are greater than 1.2 µm, more preferably greater than 1.4 µm. Typically, they are lower than 1.7 µm.

Advantageously, the optical resonator and the further
25 optical resonator have the same optical length.

Preferably, the optical resonator and the further optical resonator resonate at three different resonant frequencies substantially equal to the pump, signal and generated frequencies ω_p, ω_s, ω_g, respectively.

30 According to another embodiment of the invention, the pump, signal and generated frequencies ω_p, ω_s, ω_g fall within the same resonant frequency of the optical resonator and the

further optical resonator.

Advantageously, the optical resonator and the further optical resonator each have a free spectral range equal to or lower than 4 THz. In fact, higher values of the free spectral range would imply higher values of frequency spacing ΔF between the pump and signal radiation and, thus, an appreciable decrease of the FWM converted optical power due to chromatic dispersion. Preferably, the optical resonator and the further optical resonator each have a free spectral range equal to or lower than 1000 GHz. More, preferably, the optical resonator and the further optical resonator each have a free spectral range equal to or lower than 500 GHz. According to a variant, the optical resonator and the further optical resonator each have a free spectral range equal to or lower than 100 GHz. According to another variant, the optical resonator and the further optical resonator each have a free spectral range equal to or lower than 50 GHz. According to another variant, the optical resonator and the further optical resonator each have a free spectral range equal to or lower than 25 GHz.

The frequency spacing ΔF between the pump and signal radiation is substantially equal to the free spectral range of the optical resonators or is an integer multiple thereof.

Advantageously, the optical resonator and the further optical resonator each have a bandwidth B of at least 100 MHz. Preferably, the bandwidth B is of at least 1 GHz. More preferably, the bandwidth B is of at least 2.5 GHz. More preferably, the bandwidth B is of at least 10 GHz. Even more preferably, the bandwidth B is of at least 20 GHz. Even more preferably, the bandwidth B is of at least 40 GHz. Even more preferably, the bandwidth B is of at least 100 GHz. The above mentioned values allow the device of the invention to be used with typical telecommunications optical signal radiation modulated at 100 Mbit/s, 1, 2.5, 10, 20 and 40 Gbit/s. Preferably, the bandwidth B of the

optical resonator and of the further optical resonator is greater than the bandwidth of the optical signal radiation. More preferably, the bandwidth B of the optical resonator and of the further optical resonator is at least twice the
5   bandwidth of the optical signal radiation.

The optical signal radiation may be continuous wave (CW) signals or may be modulated in amplitude, intensity, phase, frequency, polarization, according to any conventional technique, with any conventional format (e.g. NRZ, RZ, CRZ,
10 soliton, duobinary).

Preferably, the optical resonator and the further optical resonator comprise reflectors having a power reflectivity of at least 0.5. Advantageously, the optical resonator and the further optical resonator comprise reflectors having a
15 power reflectivity lower than or equal to 0.9997 (corresponding to a transmissivity of -35dB).

Preferably, the reflectors comprised in the optical resonator have the same power reflectivity of the reflectors comprised in the further optical resonator.

20 Advantageously, the ratio FSR/B for the optical resonator and the further optical resonator is at least equal to 2.

Advantageously, the ratio FSR/B for the optical resonator and the further optical resonator is lower than or equal to 100.

25 Preferably, the optical resonator and the further optical resonator each have an optical length lower than or equal to $7500*\lambda/2$. Values of optical length higher than $7500*\lambda/2$ would involve too low FSR and bandwidth B values (see Eq. 2b below). On the contrary, values of optical length lower
30 than $40*\lambda/2$ would involve too high FSR values and, consequently, too high frequency spacing ΔF values between the pump and signal radiation and an appreciable decrease of the FWM converted optical power, due to chromatic dispersion.

According to a first embodiment of the invention, the optical resonator is a Fabry-Perot like cavity bounded by two partially reflecting mirrors. Preferably, the further optical resonator is a Fabry-Perot like cavity bounded by
5 two partially reflecting mirrors.

According to an embodiment, the partially reflecting mirrors are concentrated. According to another embodiment, they are distributed.

Advantageously, the Fabry-Perot like cavity is formed in a
10 rare-earth doped bulk medium or a rare-earth doped waveguide or optical fiber.

According to a second embodiment of the invention, the optical resonator is a microring like resonator. Preferably, the further optical resonator is a microring
15 like resonator.

According to a third embodiment of the invention, the optical resonator is formed in a photonic crystal waveguide. Preferably, the further optical resonator is formed in a photonic crystal waveguide.

20 Advantageously, the optical resonator and the further optical resonator comprise partial reflectors each having a uniform power reflectivity in the whole wavelength range of interest (for example, at the pump, signal and converted radiation frequencies).

25 Preferably, the optical power of the converted radiation is of at least 100nW.

Advantageously, the optical power of the pump radiation is of at least 100mW.

Advantageously, the optical power of the signal radiation
30 is of at least 1mW.

The non-linear material of the optical resonators is advantageously selected from the group comprising SiO_2,

TeO_2, $Al_x(GaAs)_{1-x}$, $LiNbO_3$, Si, InP, polymers, such as for example, PPV [poly(phenylene-vinylene)]or MEH-PPV (poly[2-methoxy, 5-(2'-ethyl-hexyloxy)-p-phenylene-vinylene]), and combinations thereof.

5   The structure preferably further comprises a third optical resonator cascaded to the further optical resonator. As to the features of the third optical resonator, reference is made to what disclosed above with reference to the optical resonator and to the further optical resonator.

10   Preferably, the number of optical resonators cascaded in the structure is lower than N_{max}, where N_{max} is equal to the ratio between the coherence length L_{coh} of the structure and the physical length d of each optical resonator (see Eq. 7 below).

15   Typically, the output of the device comprises an optical filter coupled at the exit of the structure, adapted to take out the radiation generated at frequency ω_g from the device and to suppress a possible residual pump radiation at frequency ω_p and a possible residual signal radiation at
20   frequency ω_s.

According to an embodiment of the invention the wavelength converter device comprises a further structure in series to the structure. In this embodiment, the device preferably comprises also a phase mismatch compensating element
25   adapted to compensate for the phase mismatch accumulated by the pump and signal radiation along the structure. Said phase mismatch compensating element is advantageously placed between the structure and the further structure.

As to the features of the further structure and the optical
30   resonators therein comprised, reference is made to what disclosed above.

Preferably, the structure and the further structures have the same number of cascaded optical resonators. Furthermore, the optical resonators of the structure are

preferably the same as the optical resonators of the further structure.

Advantageously, the structure and the further structures are substantially equal.

5   Advantageously, the phase mismatch compensating element comprises a material having a non-linear refractive index n2 lower than the non-linear refractive index of the material included in the structure and the further structure.

10   Preferably, the second order dispersion coefficients β_2 and $\hat{\beta}$ at the pump radiation frequency of the materials included in the structures and in the phase mismatch compensating element have opposite sign.

According to another embodiment, the second order
15   dispersion coefficients β_2 and $\hat{\beta}$ at the pump radiation frequency of the materials included in the structures and in the phase mismatch compensating element have the same sign.

The phase mismatch compensating element can comprise either
20   an optical dielectric waveguide, a dispersive plate or an optical fiber.

According to another aspect, the present invention relates to a use of a structure comprising a plurality of cascaded optical resonators for generating a radiation at frequency
25   ω_g through non-linear interaction of at least one pump radiation at frequency ω_p with at least one signal radiation at frequency ω_s, wherein said resonators comprise a non-linear material, resonate at the pump, signal and converted frequencies ω_p, ω_s and ω_g, and have an optical
30   length of at least $40*\lambda/2$, wherein λ is the wavelength of the pump radiation.

Preferably, the radiation at frequency ω_g is generated by four-wave mixing. More preferably, by degenerate four-wave-

mixing.

As to the features of the structure and the optical resonators reference is made to what disclosed above with reference to the wavelength converter device of the invention.

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According to a further aspect, the present invention relates to a use of a structure, comprising a plurality of cascaded optical resonators comprising a non-linear material, for altering the optical spectrum of at least one signal radiation at frequency ω_s propagating through it, by non-linear interaction of the optical signal radiation within the material of the optical resonators, wherein said optical resonators resonate at the signal radiation frequency ω_s and have an optical length of at least $40*\lambda/2$, wherein λ is the wavelength of the signal radiation.

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Preferably, the optical spectrum is altered by using self-phase modulation non-linear phenomenon.

Advantageously, the optical spectrum is altered through interaction with at least one pump radiation at frequency ω_p by using cross-phase modulation non-linear phenomenon. In this case, the optical resonators preferably also resonate at the pump radiation frequency ω_p.

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As to the features of the structure and the optical resonators reference is made to what disclosed above with reference to the wavelength converter device of the invention.

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In a further aspect thereof, the present invention relates to an apparatus for an optical network node comprising

- a routing element with at least one input port and a plurality of output ports for interconnecting each input port with at least one corresponding output port;

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- at least one wavelength converter device according to the

invention optically coupled to one of the ports of said routing element.

As to the structural and functional features of the wavelength converter device, reference shall be made to
5 what described above.

Typically, the apparatus also comprises at least one 1xK1 demultiplexer device. Said 1xK1 demultiplexer device is typically optically coupled to K1 input ports of the routing element.

10 Typically, the apparatus also comprises at least one K2x1 multiplexer device. Said K2x1 multiplexer device is typically optically coupled to K2 output ports of the routing element.

Advantageously, the routing element is selected from the
15 group comprising the following elements: add-drop, cross-connect, λ-router (i.e. wavelength selective router) and switch, and a combination thereof.

Advantageously, the apparatus also comprises N input optical fibers (with N$\geq$1). In one embodiment, the N input
20 optical fibers are optically coupled to N respective 1xK1 demultiplexer devices.

Advantageously, the apparatus also comprises M output optical fibers(with M$\geq$1 and equal to or different from N). In one embodiment, the M output optical fibers are
25 optically coupled to M respective K2x1 multiplexer devices.

In a further aspect thereof, the present invention relates to an optical communication line comprising an optical transmission path for transmitting at least one signal radiation at frequency ω_s and a wavelength converter device
30 according to the invention, wherein said wavelength converter device is optically coupled to said optical transmission path and generates a radiation at frequency ω_g by non-linear interaction between at least one pump

radiation at frequency ω_p and said at least one signal radiation at frequency ω_s.

As regards the structural and functional features of the wavelength converter device, reference shall be made to
5   what described above.

Advantageously, the optical transmission path is an optical fibre length.

Typically, said optical communication line further comprises a transmitting station for providing said at
10   least one signal radiation at a frequency ω_s.

Advantageously, the transmitting station is adapted to provide a plurality n of optical signals having frequencies ω_{s1}, ω_{s2}.... ω_{sn} differing from one another. Preferably, the transmitting station comprises a wavelength multiplexing
15   device for wavelength multiplexing the plurality n of optical signals into a single WDM optical signal and for sending said WDM optical signal along the optical communication line.

Typically, said optical communication line further
20   comprises a receiving station connected to said optical communication line.

The receiving station advantageously comprises a wavelength demultiplexer device adapted to demultiplex a WDM optical signal coming from the optical communication line.
25   Furthermore, the receiving station is typically adapted to provide the demultiplexed signals to optional further processing stages.

According to an embodiment, the optical communication line comprises an optical node comprising an apparatus according
30   to the invention, wherein said wavelength converter device of the line is comprised in the apparatus.

Further features and advantages of the present invention

will appear more clearly from the following detailed
description of a preferred embodiment, made with reference
to the attached drawings. In such drawings,

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- Figs. 1a and 1b show a schematic view of a wavelength
  converter device according to first and second embodiment
  of the invention;

- Figs. 2a and 2b show a diagram illustrating the principle
  of FWM wavelength conversion according to first and
  second embodiment of the invention;

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- Fig. 3 shows a schematic view of an ideal infinite
  periodic Fabry-Perot like multiresonator structure;

- Fig. 4 shows a plot of the ratio B/FSR versus the power
  reflectivity of the mirrors for the structure of Fig. 3
  (Fig. 4a) and a plot of the ratio v_g/v_f versus the power

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  reflectivity of the mirrors for the structure of Fig. 3
  (Fig. 4b);

- Fig. 5 is a plot of the conversion gain versus the power
  reflectivity of the mirrors for the structure of Fig. 3;

- Fig. 6 shows a plot of the maximum converted optical

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  power, which can be achieved using a single stage device
  of the invention, for different non-linear media;

- Fig. 7 shows a schematic view of a Fabry-Perot like
  multiresonator structure according to a first embodiment
  of the invention;

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- Fig. 8 shows three different ways to spatially modulate
  the refractive index of an optical waveguide in order to
  form distributed partially reflecting mirrors;

- Fig. 9 shows a schematic view of a microring like
  multiresonator structure according to a further

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  embodiment of the invention;

- Fig. 10 shows a schematic view of a photonic band gap

like structure according to a further embodiment of the invention;

- Fig. 11 shows a schematic view of a Fabry-Perot like structure in which an active medium is used according to a further embodiment of the invention;

- Fig. 12 shows a plot of the maximum converted optical power, which can be achieved using a multistage device of the invention, for different non-linear media;

- Fig. 13 shows a schematic view of a multistage device according to an embodiment of the invention;

- Fig. 14 shows a schematic view of a multistage device according to a further embodiment of the invention;

- Fig. 15 shows a schematic view of a multistage device according to a further embodiment of the invention;

- Fig. 16 shows a schematic view of a Fabry-Perot like multiresonator structure according to a further embodiment of the invention;

- Fig. 17 shows the characteristic transmission profile for the structure of Fig. 16 (Fig. 17a) and the plot of the ratio v_g/v_f versus f/FSR for the structure of Fig. 16 (Fig. 17b);

- Fig. 18 shows a schematic view of an optical communication line according to an embodiment of the invention;

- Fig. 19 shows a schematic view of an optical communication system according to an embodiment of the invention;

- Fig. 20 shows an apparatus for an optical network node according to an embodiment of the invention.

Fig. 1a shows a wavelength converter device 100 comprising

an input 1, an output 2, a pump light source 3 and a multiresonator structure 4 including a plurality of optical resonators (for simplicity, only 2 resonators 10, 20 are shown in Fig. 1a) directly connected in series.

5   Advantageously, the wavelength converter device 100 further comprises an optical isolator (not shown) for eliminating any back reflected radiation exiting the device 100 through the input 1. Typically, the optical isolator is placed between the input 1 and the first optical resonator 10.

10   Advantageously, the wavelength converter device 100 comprises an optical amplifier. Typically, the amplifier is placed at the output 2. For example, the optical amplifier is an erbium-doped fiber amplifier.

The input 1 is adapted to receive at least one signal
15   radiation at frequency ω_s.

The pump light source 3 is adapted to generate at least one pump radiation at frequency ω_p.

Furthermore, the pump light source 3 is coupled to the structure 4 through a conventional optical coupler 6.
20   Preferably, the optical coupler 6 is a wavelength selective coupler.

The structure 4 is adapted to receive said signal and pump radiation.

The optical resonators 10, 20 are made of a non-linear
25   material, each have at least two resonant frequencies substantially equal to the pump and signal frequencies ω_p and ω_s and an optical length higher than at least $40*\lambda/2$, wherein λ is the wavelength of the pump radiation.

By propagating through the structure 4, the pump and signal
30   radiation cause the generation of a converted radiation at frequency ω_g exploiting the non linear properties of the material of the optical resonators.

The output 2 is adapted to take out the converted radiation at frequency ω_g.

In a preferred embodiment of the invention, the material of the optical resonators has a non-linearity of the χ_3 type.
5   Moreover, the signal and pump frequencies ω_s and ω_p are different and the radiation at frequency ω_g is generated using the degenerate four-wave mixing (FWM) process.

Fig. 2a schematically shows the degenerate four-wave mixing process $\omega_g = 2\omega_p - \omega_s$, wherein $\omega_s = \omega_p - n\Delta\omega$, n is an integer
10 number and $\Delta\omega$ is the free spectral range of the optical resonators.

The applicant notes that, signal resonance 152 is not necessarily the first resonant frequency close to pump resonance 151, but can be shifted of an integer number n of
15 free spectral ranges; signal resonance 152 may be at a lower frequency than pump resonance 151 or at a higher frequency as well and, according to FWM properties, the converted radiation is the phase conjugated of the signal radiation and falls into the symmetrical resonance mode 153
20 with respect to the pump resonance 151. Furthermore, according to the principles of FWM wavelength conversion, in case of modulated signal radiation, the same modulation is transferred to the converted radiation.

In Fig. 2a the pump radiation frequency ω_p and the signal
25 radiation frequency ω_s are tuned to two different resonant frequencies of the optical resonators 10, 20. However, as shown in Fig.2b, they may also fall within the same resonant frequency 154 of the optical resonators 10, 20, according to another embodiment of the invention.

30 The Applicant notes that an important requirement for the device of the invention is that the optical resonators 10, 20 both resonate at the pump, signal and converted frequencies. However, it is not necessary that they have the same finesse F ($F=FSR/B$). As shown below (see Eq. 2),

this means that the optical resonators 10, 20 may have
different values of power reflectivity R and optical
length. However, in a preferred embodiment they have the
same optical length. In a further preferred embodiment the
5   reflectors included in the optical resonators 10, 20 have
the same power reflectivity.

Some basic notions for degenerate FWM are now briefly
illustrated.

For a non-resonant waveguide structure and in the
10 hypothesis of slowly varying envelope, undepleted pump,
negligible self phase modulation, lossless media, the
spatial evolution of the optical power P_c of the FWM
converted radiation satisfies the following equation:

$$P_c(z) = \gamma^2 P_p^2 P_s z^2 sinc^2\left(\frac{\Delta k \cdot z}{2}\right) \qquad (1)$$

15 where z is the spatial coordinate, P_p is the optical pump
power and P_s is the optical signal power. γ is a
coefficient that depends on the non-linear refractive index
n_2 and on the waveguide effective area A_{eff}, while $\Delta k = 2k_p - k_s -
k_c$ takes into account the impact on frequency conversion
20 efficiency of the phase mismatch due to the different wave
vectors of interacting fields. Since γ is typically a small
number (about $1.5 \cdot 10^{-3} m^{-1} W^{-1}$ in a silica fiber) high pump
power (about 1W) and extremely long device (of the order of
Km) are generally required.

25 From this point of view the Applicant notes that the use of
an optical resonator for carrying out a FWM process leads
to a double advantage.

First of all, a radiation, whose frequency coincides with a
resonant frequency of the optical resonator, spends much
30 more time through the resonator of physical length L_f than
through a non-resonant waveguide structure of the same
length. This effect derives from the fact that the group
velocity v_{in} within the optical resonator is lower than the
group velocity v_{out} within a non-resonant waveguide

structure. As a consequence the interaction time between an optical pump radiation and a signal radiation is considerably increased when both optical radiation are suitably tuned near a resonant frequency. The more the
5 propagation is slowed ($v_{in} < v_{out}$), the longer the interaction time within the resonator. Since FWM is an interaction time dependent process, the conversion efficiency in an optical resonator is higher than in an equivalent non-resonant waveguide structure of the same
10 physical length L_f.

Moreover, within the optical resonator, a radiation whose frequency coincides with a resonant frequency of the optical resonator, has a power P_{int} strongly enhanced with respect to the power P_{out} within a non-resonant waveguide
15 structure. This effect too is due to the above mentioned slowed propagation group velocity and the more the propagation is slowed, the higher P_{int} compared to P_{out}. Since FWM is an intensity dependent process, the conversion efficiency in an optical resonator is further improved
20 compared to that of an equivalent non-resonant waveguide structure of the same physical length L_f.

The FWM process in an ideal infinite periodic structure made of cascaded optical resonators is now described.

As also described hereinafter in more detail, the cascaded
25 optical resonators can be made from a series of directly coupled Fabry-Perot like cavities, optical microrings or a photonic band gap (PBG) waveguide with proper defects therein.

In the following description the main topics of an ideal
30 infinite Fabry-Perot like multiresonator structure is described, even if the same teachings can be applied to optical microring and PBG structures.

Fig.3 shows said multiresonator structure wherein partially reflecting mirrors 72 are placed at a distance d from each

other into a substrate 71 of refractive index n.

This multiresonator structure has a periodic spectral response. Only a radiation whose spectrum lies inside a pass-band resonance of the structure can propagate;

5   otherwise the radiation is backward reflected.

Important parameters of this kind of multiresonator structure have been theoretically determined by the Applicant.

The bandwidth B of such structure is given by

10

$$B = \frac{2FSR}{\pi} arcsin(t) \qquad (2)$$

where t is the field transmission coefficient of each mirror 72 and $FSR=c/2nd$ (Eq. 2b) is the free spectral range, i.e. the frequency difference between two consecutive resonant frequencies of the multiresonator

15   structure. In Eq. 2b, nd is the optical length of each optical resonator.

Thus, the selective behaviour of the structure, expressed by the finesse $F=FSR/B$, only depends on the power reflectivity R of the mirrors 72 (where $R=1-t^2$).

20   As shown in Fig.4a, the ratio between the bandwidth B and the FSR, i.e. the inverse of the finesse F, decreases versus an increasing mirror power reflectivity R.

Since intra-resonator propagation constant β is a function of ω, the multiresonator structure introduces a periodic

25   frequency dispersion. The group velocity, defined as $d\omega/d\beta$, is found to be at each resonant frequency

$$v_g(f_0) = \frac{c}{n}t = v_f t \qquad (3)$$

where $v_f =c/n$ is the phase velocity of the optical field in the intra-resonator medium and f_0 is the resonant frequency

30   of the structure. As the transmission coefficient is always less than unity, the group velocity within the structure is

always lower than the phase velocity.

In Fig.4b the ratio between the reduced intra-resonator group velocity $v_g(\omega_0)$ and the phase velocity v_f is plotted versus the power reflectivity R of mirrors 72.

5   As shown in Fig.4b, the ratio $v_g(\omega_0)/v_f$ decreases versus an increasing mirror power reflectivity R.

Therefore, high reflectivity mirrors 72 may practically reduce up to zero the group velocity of a propagating pulse (thereby increasing the conversion efficiency), even though
10 this effect involves a bandwidth B reduction.

The Applicant found that the above mentioned results still hold for a finite quasi periodic multiresonator structure, when a sufficiently large number of resonators are employed (e.g. 5 resonators). However, the advantages of the
15 invention stand up also for a structure with only two cascaded resonators (see Fig. 6).

A good estimate for the conversion gain G (that is, the ratio between the FWM converted optical power $P_{c,mrs}$ in a multiresonator structure and the FWM converted optical
20 power P_c in a non-resonant waveguide structure using the same pump and signal radiation and the same non linear medium) of the multiresonator structure of Fig. 3 is given by

$$G \cong \left(\frac{1+t^2}{2t^2}\right)^2 \qquad\qquad (4)$$

25 where t is the field transmission coefficient of each mirror.

Fig. 5 shows the behaviour of the conversion gain G versus the mirror power reflectivity R. An extremely high conversion enhancement can be achieved using high
30 reflectivity mirrors.

Taking into account Eq.(1), the FWM converted optical power

$P_{c,mrs}$ for an ideal infinite multiresonator structure is given by

$$P_{c,mrs} = \gamma^2 P_p^2 P_s z^2 sinc^2\left(\frac{\Delta\beta \cdot z}{2}\right)G \tag{5}$$

where z is the spatial coordinate and $\Delta\beta=2\beta_p-\beta_s-\beta_c$ is the intra-resonator phase mismatch.

Eq.(4) and (5) hold in the above stated hypothesis of slowly varying field envelope, undepleted pump, negligible self phase modulation and lossless media.

The maximal length of the multiresonator structure is limited by the presence of the phase mismatch $\Delta\beta$ between interacting fields. The phase mismatch $\Delta\beta$ derives from chromatic dispersion, waveguide dispersion, non linear cross phase modulation and self phase modulation. The coherence length of the structure, that is the length after which power starts to turn back from the converted radiation to the pump radiation, is defined as

$$L_{coh} = \frac{\pi}{|\Delta\beta|} = \frac{\pi}{|\Delta k|}t \tag{6}$$

where $\Delta k=2k_p-k_s-k_c$ is the phase mismatch term in a non-resonant waveguide structure. Thus, the coherence length in the multiresonator structure is reduced with respect to a non-resonant waveguide structure.

Since highly non linear materials often show a highly dispersive behaviour, chromatic dispersion is typically the dominant factor which limits the coherence length. Non linear cross phase and self phase modulation should be contemplated in a high power conversion process or when chromatic dispersion is very low.

The maximum physical length L_{max} of the multiresonator structure is preferably lower than or equal to the coherence length L_{coh}. Therefore, the maximum number of resonators that can be cascaded to form the multiresonator structure preferably is

$$N_{max} = \frac{L_{max}}{d} = \frac{L_{coh}}{d} = \frac{\pi t}{|\Delta k| d}. \qquad (7)$$

According to Eq.(2) the physical length d of each resonator may be written as

$$d = \frac{c}{2nFSR} = \frac{c}{n} \frac{arcsin(t)}{\pi B} \qquad (8)$$

5   and substituting Eq.(8) into Eq.(7) N_{max} is given by

$$N_{max} = \frac{\pi^2 n B}{|\Delta k| c}. \qquad (9)$$

where the approximation $arcsin(t) \approx t$ used in deriving Eq.(9) holds for highly reflective mirrors.

The chromatic dispersion term Δk can be expressed in terms
10   of the frequency detuning ΔF (that is, the frequency spacing $|f_s - f_p|$) between the signal radiation and the pump radiation as

$$\Delta k \approx \beta_2 (2\pi \Delta F)^2 \qquad (10)$$

where β_2 is the second order dispersion coefficient at the
15   pump radiation frequency. Introducing the expression of Δk, Eq.(9) becomes

$$N_{max} = \frac{nB}{4c|\beta_2|(\Delta F)^2}. \qquad (11)$$

Equation 11 relates the maximum number of cavity N_{max} to the bandwidth B, the frequency detuning ΔF and the material
20   dispersion β_2.

The ratio between the maximum converted output power $P_{c,mrs}$ and input powers P_p and P_s (that is, the maximum FWM efficiency) may be derived from Eq.(4),(5) and (6). Substituting into Eq.(5) the coherence length L_{coh} from
25   Eq.(6), said ratio is given by

$$\frac{P_{c,mrs}}{P_p^2 P_s} = \left(\frac{2\gamma}{\Delta k}\right)^2 \left(\frac{1+t^2}{2t}\right)^2 \qquad (12)$$

The number of cavities necessary to obtain such a power level is just equal to N_{max}.

The Applicant notes that the first factor uniquely depends

on non-linear and dispersive material properties while the second factor is given by the multiresonator structure.

To sum up:

a) the bandwidth B and the FSR of the multiresonator structure decrease versus an increasing physical length d of each resonator [see Eq. 2 and Eq. 2b ($FSR=c/2nd$)];

b) the inverse of the finesse F and the bandwidth B of the multiresonator structure decrease versus an increasing mirror power reflectivity R (see Eq. 2 and fig. 4a);

c) the conversion gain G increases with an increasing mirror power reflectivity R (see Eq. 4 and fig. 5);

d) the FWM converted optical power $P_{c,mrs}$ in the multiresonator structure increases with an increasing gain G and an increasing distance z (see Eq. 5);

e) for a multiresonator structure, the spatial coordinate z is equal to $N*d$, wherein N is the number of cascaded resonators.

Following what said above, while designing a wavelength converter device of the invention, the power reflectivity R and physical length d of each resonator can be selected according to the desired values for finesse F (B/FSR) and bandwidth B of the structure (that is, according to WDM optical communication system requirements, e.g. the bandwidth of the signals and the channel spacing) while the number of cavities N can be selected so as to obtain the desired value for FWM converted optical power $P_{c,mrs}$.

Therefore, in the device of the invention, even if external factors constrain the selection of the power reflectivity R and the physical length d of each resonator, desired values of converted optical power and conversion efficiency can still be obtained by suitably selecting the number N of cavities (with the only restriction that N is preferably

less than N_{max}).

Accordingly, with respect to a conventional wavelength converter device using the four-wave mixing process in a single optical resonator, the multiresonator structure of
5   the invention has an extra degree of freedom (i.e. the number N of resonators) which allows both an efficient and flexible wavelength converter device to be obtained.

Fig. 6 shows the maximum converted optical power $P_{c,mrs}$ versus the number N of resonators when different non-linear
10   materials (SiO_2, TeO_2 and $Al_{0.2}GaAs_{0.8}$) are used to perform FWM wavelength conversion.

The curves of Fig. 6 were obtained through a computer simulation based on Eq. 5 for a bandwidth B of 20GHz, a frequency detuning ΔF of 2THz, 200GHz spaced WDM channels,
15   an effective area A_{eff} of the waveguide of 10 μm^2 and pump and signal radiation powers respectively of 100mW and 10mW.

For a AlGaAs multiresonator structure the number of cascaded resonators is preferably less than 11. As shown in Fig. 6, a higher number of resonators may lead to a
20   decrease of the FWM converted optical power, due to the high second order dispersion coefficient $\beta_2 \sim 1240$ ps^2/Km. A TeO_2 ($\beta_2 \sim 52$ ps^2/Km) multiresonator structure preferably has less than 170 cascaded resonators and a SiO_2 ($\beta_2 \sim -25$ ps^2/Km) multiresonator structure preferably has less than
25   about 240 cascaded resonators.

It is worthwhile noting that AlGaAs has a non-linear refractive index n2 more than ten times higher than TeO_2. Hence, a slightly inferior converted optical power can be obtained using an extremely low number of resonators.

30   Resuming the description of the device of Fig. 1, the pump light source 3 is a conventional laser or light emitting diode source.

Advantageously, the output 2 comprises an optical filter

(not shown) suitable to let the converted radiation at
frequency ω_g exit from the device 100 and to suppress any
residual pump and any residual signal radiation.

When the pump and signal radiation propagate through the
5   structure 4 in the opposite direction, the device 100
preferably comprises also an optical isolator (not shown),
placed between the input 1 and the first optical resonator
10, to suppress the counter-propagating residual pump while
any residual signal radiation is suppressed by the filter.

10   The input 1 and output 2 are each advantageously connected
to a fibre pigtail for facilitating the connection of the
device 100 to other optical fibre elements.

The non-linear material of the optical resonators 10, 20
can be for example selected from the group comprising SiO_2,
15   TeO_2, $Al_{0.2}GaAs_{0.8}$, polymers (for example, PPV), Si and InP.

The structure 4 can be made from either a waveguide or a
bulk multilayer.

Possible waveguides are dielectric waveguides (buried, rib,
ridge or diffused), photonic band gap (PBG) waveguides or
20   optical fibers.

The cascaded optical resonators 10, 20 can be made from
cascaded Fabry-Perot cavities, cascaded optical microring
resonators or proper defects in a photonic band gap
waveguide.

25   Fig.16 shows an example of a finite multiresonator
structure 4 made of eight cascaded optical resonators.

In said structure 4, nine partially reflecting mirrors 92
are inserted into a waveguide integrated in a substrate 91
of refractive index n at a distance d from each other. The
30   relatively high impedance of the sequence of resonators is
preferably matched to the input and output of the device
100 by introducing at the beginning and at the end of the

structure 4 sections having mirrors 92a, 92b with lower reflectivity.

The suitable power reflectivity profile of the mirrors can be obtained through known methods of synthesis of selective
5 bandpass filters based on directly coupled resonator.

For example, using the synthesis technique disclosed in the above mentioned article by A. Melloni et al. ("Synthesis of direct-coupled resonators bandpass filters for WDM systems", Journal of Lightwave Technol., Vol. 20, No. 2,
10 Feb. 2002, pages 296-303), the following power reflectivity profile can be obtained for an eight resonator Chebyshev like structure with a finesse F equal to 5 . The power reflectivity R of the internal mirrors 92c is 0.88 while the power reflectivity R of the first 92a and the second
15 92b mirrors (as well as the power reflectivity R of the last two mirrors 92a and 92b) is respectively 0.28 and 0.765 for the above mentioned impedance matching requirements. As this reflectivity profile performs a 20dB in band return loss (defined as the ratio between the back
20 reflected optical power and the input optical power), signals tuned closely to a resonant frequency may propagate without noticeably attenuation. Out of band signals are completely reflected because of a more than 60dB stop band rejection.

25 Fig. 17a shows the power transmittivity (defined as the ratio between the output optical power and the input optical power) versus f/FSR (wherein f is the frequency), for the structure of Fig.16.

FIG.17b shows the ratio between the phase velocity and the
30 group velocity versus f/FSR, for the structure of Fig.16. As shown in Fig. 17b, in band signals are delayed nearly three times compared to signals propagating in a non-resonant structure, in good agreement with theoretical results. As a result a signal whose frequency lies near a
35 resonant frequency ω_o spends more time travelling through

the multiresonator structure 4 than it takes travelling
through an equivalent non-resonant waveguide structure of
the same physical length L_f. Thus, when the FWM wavelength
conversion takes place inside the multiresonator structure
5   4, the interaction time is increased as well as the
propagation velocity is reduced. Such enhancement is about
$1/t$, where t is the inner mirror field transmission
coefficient.

Fig. 7 shows a Fabry-Perot like multiresonator structure 4,
10 according to an embodiment of the invention, comprising an
optical waveguide 120 wherein a series of equi-spaced
partially reflecting mirrors 124 are inserted in order to
form a plurality of cascaded optical Fabry-Perot like
cavities. The optical length Lo of each cavity ($Lo=d*n_{eff}$,
15 wherein d is the distance between two consecutive mirrors
and n_{eff} is the effective refractive index of the material
of which the waveguide 120 is made) is of at least $40*\lambda/2$,
wherein λ is the wavelength of the pump radiation.

The partially reflecting mirrors 124 can be either
20 concentrated (that is, much shorter than the wavelength in
the medium) or distributed (that is, several quarter of
wavelengths long). The concentrated reflector can be
obtained by means of an abrupt discontinuity between two
materials with a strong refractive index difference (for
25 example, metal-glass). The distributed reflector can be
achieved by a 1D, 2D or 3D periodical structure. For
example, the 1D structure can be made of a conventional
Bragg grating.

As well known in the art, forward and backward waveguide-
30 mode-coupling are induced in a Bragg grating by
periodically varying the effective refractive index n_{eff}.
Said periodical variation may be achieved by spatially
modulating the n_{eff}. For example, a lateral corrugation
(FIG.8a) or an upper corrugation (FIG.8b) — induced by
35 periodically etching the optical waveguide spatial profile
— can be used. In fact, such periodical change in the

waveguide width leads to a periodic longitudinal modulation of the n_{eff}. Otherwise a direct periodical variation of n_{eff} can be induced by the exposure of a photosensitive medium in a pattern of diffracted UV light (FIG.8c). The
structures of Fig.8 may be suitably combined and other methods to perform periodical variation of n_{eff} may also be used.

The Bragg gratings may be of the chirped type. This allows a broader reflectivity band to be achieved.

The Bragg gratings may be of the apodized type.

As already disclosed above, wavelength conversion may be performed using degenerate four wave mixing process in the non-linear medium of the waveguide 120. Input into the structure 4 are the pump radiation at frequency ω_p and the
signal radiation at frequency ω_s. The pump frequency ω_p and the signal frequency ω_s are tuned as close as possible to a resonance mode of the cascaded optical resonators, preferably as close as possible to the center of the resonance mode. As the radiation propagates inside the non-
linear medium, a converted radiation is generated within the structure 4 by FWM between the pump radiation and the signal radiation. The frequency of the converted optical radiation is $\omega_c = 2\omega_p + \omega_s$ or $\omega_c = 2\omega_p - \omega_s$. Then, the pump, signal and converted radiation leave the structure 4 as shown in
Fig. 7.

In Fig. 7 wherein the pump and signal radiation travel in the same direction, forward FWM is performed. However, in general, backward FWM can also be performed, wherein the pump and signal radiation propagate through the structure 4
in the opposite direction.

In one particular embodiment of the structure 4 of Fig. 7, the structure 4 comprises eleven semiconductor Fabry-Perot like resonators obtained by inserting in a $Al_{0.2}GaAs_{0.8}$ waveguide twelve equi-spaced partially reflecting mirrors.

The seven inner mirrors have a power reflectivity of about 0.97, the first and the last impedance matching mirrors have a power reflectivity of about 0.55 while the second and the last but one impedance matching mirrors have a

5   power reflectivity of about 0.94. This mirror reflectivity profile performs a Chebyshev-like multiresonator structure with a bandwidth B of 20GHz and FRS of 200GHz. Due to phase mismatch, the maximum frequency detuning Δf is preferably of 2THz. The waveguide has an effective refractive index

10   n_{eff} of 3.3. Each cavity has a physical length d of 217µm and, neglecting reflector thickness, the whole structure has a physical length of about 2.39mm. The waveguide has an effective area A_{eff} of 10 µm^2. A continuous 100mW pump radiation is tuned at one resonant mode of the structure

15   (f_p = 196 THz). A modulated 10mW signal radiation has a frequency f_s tuned at another resonant mode of the structure (f_s = 194 THz) and is 2THz shifted with respect to the pump radiation, according to the case shown in Fig.2a. The pump and signal radiation co-propagate through the

20   structure 4 and both enter the device 100 from the input 1. A third converted wave is generated by FWM at frequency f_c (f_c=198THz). No significant power is backward reflected thanks to a 20dB in band return loss of the structure. The converted optical power $P_{c,mrs}$ is 5.9µW (about −22dBm,

25   corresponding to the point A of Fig.6). By using Eq. 4 and 5, more than 22dB gain G is obtained compared to a 2.39mm non-resonant waveguide structure.

According to further embodiments of the present invention, in the structure 4 a different number of cavities as well

30   as different substrates may be used.

Fig. 9 shows another embodiment of the invention according to which the structure 4 comprises a plurality of direct-coupled optical microring resonators 210.

Optical microring resonators 210 are directly coupled to

35   each other and to input/output waveguides 212. According to the above mentioned article by A. Melloni et al.

("Synthesis of direct-coupled resonators bandpass filters
for WDM systems", Journal of Lightwave Technol., Vol. 20,
No. 2, Feb. 2002, pages 296-303), the transfer function of
this structure is the same as a Fabry-Perot like
5   multiresonator structure. Thus, the previously explained
theory holds also in this case. A microring differs from a
Fabry-Perot cavity only for having the forward and backward
input/outputs ports 212 all physically distinct (with the
consequent advantage that the reflected radiation is
10 separated from the incoming radiation thereby avoiding the
use of circulators or isolators). The pump and signal
radiation are supplied by an optical fiber 211a to the
input port 212a. If the frequencies of the pump and signal
radiation are launched into the structure at two resonant
15 frequencies of the resonators, both radiation are coupled
from input waveguide 212 to the first ring 210a, from the
first ring 210a to the second ring 210b and so on towards
the output ports 212c and 212d. The pump and signal
radiation are coupled to port 212c if N is odd while to
20 port 212d if N is even, where N is the number of cascaded
microrings. Port 212b is the uncoupled output port for out
of resonance input radiation.

For a cascaded microring resonator structure, the optical
length of the resonator is defined as $n_{eff}*\pi r$, wherein n_{eff}
25 is the effective refractive index of the material of which
the structure is made of and r is the microring radius.

Fig. 10 shows another embodiment of the invention according
to which the structure 4 comprises a photonic crystal
waveguide 221. The photonic crystal waveguide 221 is
30 obtained eliminating one or more row of defects in a two-
dimensional (2D) or three-dimensional (3D) photonic crystal
lattice 220. Clearly, only the frequencies within the
photonic bands are allowed to propagate through the
waveguide. In Fig. 10, a 2D square lattice is shown even if
35 different and more sophisticated lattices such as the
hexagonal lattice can be used.

Single or multiple defects (224a to 224z) act as partially
reflecting mirror so as to form cascaded cavities 225a to
225z. The power reflectivity of the mirrors depends on the
dimension of the defects themselves. The transfer function
5   of such a structure is the same as a Fabry-Perot like
multiresonator structure. Thus, the previously explained
theory holds also in this case. The pump and the signal
radiation are supplied by an input optical fiber 222 to an
input port of the waveguide 221. If the frequencies of the
10 pump and signal radiation are launched into the structure
at two resonant frequencies of the resonators, both
radiation propagate towards an output port of the waveguide
221. As in the Fabry-Perot like multicavity shown in Fig.
7, also in this embodiment the forward and backward
15 input/outputs ports are not physically distinct. Pump,
signal and converted output radiation can be collected
using an optical fiber 223.

Fig. 11 shows another embodiment of the invention according
to which the structure 4 comprises a plurality of cascaded
20 Fabry-Perot like cavities formed in a rare-earth doped bulk
medium or a rare-earth doped waveguide 230, (e.g. erbium
doped). A pumping light beam tuned within the active
medium absorption band leads to a stimulated emission
amplification of a general signal travelling through such
25 structure. When the pump and signal radiation involved in
the FWM process fall into the active medium gain band, the
wavelength conversion process is further enhanced (as
explained, for example, by EP 0 981 189). A laser source
233 is used as pumping light beam for the active medium.
30 Such pumping light beam is preferably tuned far away from
the reflectivity band of the mirrors of the cavities (for
example far away from the Bragg grating band) so that it
does not experience the resonator-like propagation. The
pumping light beam is coupled to an input optical fiber
35 231a by an optical coupler 232a and an optical fiber
pigtail 234a, while a second optical coupler 232b is used
to extract the pumping light beam from an output optical

fiber 231b at the exit of the structure 4.

The Applicant notes that, although in the device 100 the maximum number of resonators is limited by the phase mismatch (see Eq. 9), the converted optical power $P_{c,mrs}$ can

5   be further increased with a multistage device 100 according to another embodiment of the invention.

The multistage device 100 comprises an input 1, an output 2, a pump light source 3, an optical coupler 6, a plurality of cascaded multiresonator structures 4 and a plurality of

10   phase mismatch compensating elements 5 interspersed with the structures 4 as shown in Fig. 1b.

As to the features of the input 1, the output 2, the pump light source 3, the optical coupler 6, each multiresonator structure 4, reference is made to what already disclosed

15   above.

The phase mismatch compensating elements 5 are adapted to compensate for the phase mismatch between the pump and signal radiation at the exit of each structure 4.

The pump, signal and generated radiation which leave the

20   first structure out of phase, propagate through the first phase mismatch compensating element without non-linear interaction, enter the second structure with the opportune relative phase, and so on till the last structure. The compensating element is preferably made of a linear

25   material so as to prevent FWM from taking place. In fact, any non-linear interaction would transfer power back from the converted radiation to the pump radiation thereby reducing wavelength conversion efficiency.

According to Eq. 5, by doubling the distance z, and hence

30   the number N of resonators, the output converted optical power is increased of 6dB. Thus, each additional structure 4 implies an output converted optical power increase of 6dB (by suitably selecting the optical power of the pump radiation).

Fig. 12 shows the performance of a multistage device 100. With reference to each material, each structure is equal to the one described with reference to Fig. 6. For example, in a AlGaAs multistage device a phase mismatch compensating element is preferably used after 11 resonators. In one embodiment, a 220 resonator AlGaAs multistage device preferably comprises 20 structures alternated with suitable designed phase mismatch compensating elements. In Fig. 12 the point A is marked to compare the performance of a multistage device with respect to the single stage AlGaAs device disclosed with reference to Fig. 6.

The phase mismatch compensating element can be designed taking into account the following considerations.

Let $\Delta\phi$ be the phase mismatch accumulated between the pump and signal radiation at the exit of each structure. Using Eq.10, the general expression for $\Delta\phi$ may be expressed as

$$\Delta\phi \approx \frac{\Delta k\, L}{t} \approx \beta_2 (2\pi\,\Delta F)^2 \frac{L}{t} \qquad (13)$$

where β_2 is the second order dispersion coefficient (at the pump radiation frequency) of the material the structure is made of and L is the physical length of the structure itself (wherein L may be less than or equal to L_{coh}). If the wavelength converter device is used in a WDM communication system, not all WDM channels experience the same phase mismatch. In fact, the higher the detuning ΔF from the pump wave, the greater the phase mismatch $\Delta\phi$. Thus, the phase mismatch compensating element should introduce a frequency dependent compensating term $\Delta\hat{\phi}$ that satisfies the condition

$$\Delta\phi + \Delta\hat{\phi} = 2M\pi \qquad (14)$$

where M is an integer.

Different approaches may be followed in order to achieve a compensating element. For instance, a linear element made

of a material having a $\widehat{\beta}$ opposite in sign with respect to β_2 may be used. If $\widehat{L}$ is the physical length of such a phase mismatch compensating element, the phase term introduced is $\Delta\widehat{\phi} = \widehat{\beta}_2 (2\pi \Delta F)^2 \widehat{L}$. Since the sign of $\Delta\widehat{\phi}$ is opposite to the

5   sign of $\Delta\phi$, we will refer to it as *backward rephasing*. Substituting the expressions of $\Delta\phi$ and $\Delta\widehat{\phi}$ into Eq.(14), we obtain the length $\widehat{L}$ of the compensating device

$$\widehat{L} = \left|\frac{\beta_2}{\widehat{\beta}_2}\right| \frac{L}{t} \qquad\qquad (15)$$

It should be noted that in the case of backward rephasing

10   the physical length $\widehat{L}$ of the phase mismatch compensating element does not depend on the frequency detuning ΔF. This result derives from the fact that in the case of backward rephasing Eq.14 admits a solution for $M=0$. It follows that one compensating element is enough to rephase all the WDM

15   channels exiting from a multiresonator structure and the multistage device may be designed to wavelength convert a plurality of WDM optical channels.

Also, a phase mismatch compensating element made of a material having a $\widehat{\beta}$ with the same sign as β_2 may be used.

20   If $\widehat{L}$ is the physical length of such a phase mismatch compensating element, the phase term introduced is $\Delta\widehat{\phi} = \widehat{\beta}_2 (2\pi \Delta F)^2 \widehat{L}$. Since in this case the phase mismatch compensating element adds a further frequency dependent dephasing term of the same sign as $\Delta\phi$, we will refer to it

25   as *forward rephasing*. When the total dephasing reaches a multiple of 2π, the pump, signal and generated radiation return to be in phase again and may enter the following structure of the multistage device. From Eq. 14 the length $\widehat{L}$ of the compensating device is achieved:

30   $$\widehat{L}(\Delta F) = \frac{2M\pi - \Delta\phi(\Delta F)}{\widehat{\beta}_2 (2\pi \Delta F)^2 \widehat{L}} \qquad\qquad (16)$$

where $\Delta\phi(\Delta F)$ is the phase mismatch at the exit of each structure, according to Eq.13. It should be noted that in this case the length $\widehat{L}$ of the compensating device always

depends on the detuning ΔF. In fact, Eq.(14) does not admit a solution for $M=0$ and consequently, once $\hat{L}$ is chosen, forward rephasing works only at a fixed detuning ΔF. Therefore a multistage device with forward rephasing

5   compensating elements operates an efficient wavelength conversion only for one WDM channel spaced ΔF from the pump radiation. If more than one WDM channel has to be compensated, backward rephasing is preferred and consequently different materials have to be used for the

10 structures and the compensating elements.

Fig. 13 shows an embodiment of a multistage device 100 of the invention comprising two structures 121a and 121b and a phase mismatch compensating element 181 inserted between the two structures 121a, 121b. The phase mismatch

15 compensating element 181 is a dielectric optical waveguide. Such waveguide may be made of the same material as the structures 121a, 121b (forward rephasing), or of a different material (forward or backward rephasing depending on the signs of β_2 and $\hat{\beta}$). As shown in Fig. 13, the

20 compensating waveguide 181 is wider than the waveguides of the structures. This allows non-linear field interactions to be prevented because the non-linear coefficient γ decreases with an increasing waveguide effective area A_{eff}. A further reduction of the non-linear coefficient γ (and,

25 thus, of the non-linear field interactions) may be achieved by suitably selecting a material having a non-linear refractive index n2 lower than the non-linear refractive index n2 of the material of the structures 121a, 121b.

As the widening of the waveguide transversal dimension may

30 excite higher order modes, the multistage device 100 of Fig. 13 preferably further comprises tapered input and output transition sections 182a, 182b. These sections are designed according to conventional techniques so as to obtain an adiabatic transition and reduced power losses.

35 Pump and signal radiation are supplied to the multistage device 100 from an input optical fiber 183a and, after

propagating through the first non linear structure 121a,
enter the phase mismatch compensating element 181 passing
through the input tapered section 182a. After propagating
through the phase mismatch compensating element 181, they
5   enter the second non linear structure 121b passing through
the output tapered section 182b. Then, pump, signal and
converted radiation leave the structure 121b through an
output optical fiber 183b. An optical filter (not shown)
will suppress any residual pump and signal radiation.

10 The lengths of the waveguide 181 and of the input and
output tapered sections 182a, 182b are adjusted according
to Eq. 15 or Eq. 16 in order to obtain the desired relative
phase between the pump and signal radiation at the
beginning of the second structure 121b.

15 For example, referring to the structure made of $Al_{0.2}GaAs_{0.8}$
described above with reference to Fig. 7 – whose second
order dispersion coefficient β_2 is positive ($\beta_2 \sim 1240$
ps^2/Km at 1530 nm) – the compensating waveguide 181 may be
made of $Al_{0.2}GaAs_{0.8}$ thereby obtaining a forward rephasing
20 compensating element. Using Eq. 16, the length $\bar{L}$ of such a
compensating waveguide 181 is about 18mm for a detuning
$\Delta F=2$ THz. Alternatively, the compensating waveguide 181 may
be made of a material having a negative value of β_2, such
as SiO_2 ($\beta_2 \sim -25$ ps^2/Km at 1530 nm) so as to obtain a
25 backward rephasing compensating element.

Even if Fig.18 shows a two stage device 100 with two
structures 121a, 121b and one compensating element 181, a
different number of structures and compensating elements
may be employed.

30 Fig. 14 shows a further embodiment of a multistage device
100 of the invention comprising four structures 121a to
121d arranged in parallel in a substrate 191 and three
phase mismatch compensating elements 192a to 192c inserted
in series between one structure and the other. In this
35 embodiment the four structures 121a to 121d are made of

$Al_{0.2}GaAs_{0.8}$ while compensating elements 192a to 192c consist each of a SiO_2 optical fiber (backward rephasing). Pump and signal radiation may be supplied to the device 100 through an input optical fiber 193a, propagate through the
5   structure 121a from the front facet to the back facet, enter the phase mismatch compensating fiber 192a, hence propagate through the second structure 121b from the back facet to the front facet and so on. Finally pump, signal and converted radiation leave the multistage device 100
10   through an output optical fiber 193b. The length of each fiber 192 is adjusted according to Eq. 15 in order to obtain the desired relative phase between the pump and signal radiation at the beginning of each structure 121. Because of the small absolute value of β_2 in SiO_2 with
15   respect to $Al_{0.2}GaAs_{0.8}$, the length $\hat{L}$ of each compensating fiber 192 is about $66.2\,cm$, while the length L of each structure 121 is about $2.39\,mm$.

In order to reduce the length $\hat{L}$ of the compensating elements 192, highly dispersive SiO_2 optical fibers as well
20   as optical fibers made of other materials may be used. Moreover, when the structures 121 are made of a material with a negative second order dispersion coefficient β_2, compensating fibers 192 made of a material having a positive value of β_2 may be used to perform backward
25   rephasing.

Fig. 15 shows a further embodiment of a multistage device 100 of the invention comprising two structures 121a, 121b and one phase mismatch compensating element consisting of a dispersive plate 201 inserted between two structures 121a,
30   121b. An input optical waveguide 202a and an output optical waveguide 202b may be introduced between the dispersive plate 201 and each structure 121a, 121b for improving the manufacturing (lapping and cut) process. The dispersive plate 201 and the length of each optical waveguide 202a,
35   202b are adjusted in order to obtain the desired relative phase between the pump and signal radiation at the

beginning of the second structure 121b. Pump and signal radiation are supplied to the device 100 through an input optical fiber 203a. Another optical fiber 203b is used as output port for pump, signal and converted radiation.

5   A dispersive plate is a plate having high chromatic dispersion value with respect to the non-linear material of the structures 121a, 121b. Preferably, it has chromatic dispersion value ten times higher.

Of course, even if Fig. 15 shows a two stage device, a
10   different number of cascaded structures and dispersive plates may be employed.

The wavelength converter device of the invention can be used for avoiding a conflict of wavelengths in a node of a WDM optical network wherein signals at different
15   wavelengths are routed towards other nodes of the network (S.J.B. Yoo, "Wavelength conversion technologies for WDM network applications", Journal of Lightwave Technology, Vol. 14, No. 6, June 1996, pages 955-966). In fact, in such a node it may occur that two signals having the same
20   wavelength (or frequency) have to be routed towards the same output and that a device suitable to convert the wavelength of one of the two signals into another wavelength, before routing the two signals towards the same node output, is required.

25   Moreover, since the converted radiation is the phase conjugated of the signal radiation and falls into the symmetrical resonance mode with respect to the pump resonance (see Fig. 2), the wavelength converter device of the invention can also be used as spectral inverter of a
30   signal radiation with respect to a pump radiation.

For example, such spectral inverter can be used for compensating the chromatic dispersion of a signal or of a grid of WDM signals in an optical communication line or system. In the case of a grid of WDM signals, the spacing

in frequency of the grid of WDM signals must be substantially equal to the free spectral range of the wavelength converter device or to an integer multiple thereof.

5   Even if the wavelength converter device of the invention has been disclosed with reference to the wavelength conversion through degenerate FWM process, it is clear that it can also be suitably designed to perform wavelength conversion through non-degenerate FWM process or any 10   another of the above mentioned parametric processes.

Furthermore, the device of the invention, can also be used to alter (e.g. to broaden) the optical spectrum of a signal radiation propagating through it according to the well known self-phase modulation (SPM) or cross-phase modulation 15   (XPM) non-linear phenomena.

More in particular, SPM refers to the self-induced phase shift experienced by an optical field during its propagation in a non-linear medium. Among other things, SPM is responsible for spectral broadening of ultrashort pulses 20   and the existence of optical solitons in the anomalous-dispersion regime of the non-linear medium. On the contrary, the XPM refers to the non-linear phase shift of an optical field induced by a copropagating field at different wavelength. Among other things, XPM is 25   responsible for spectral broadening of copropagating optical pulses (see G.P. Agrawal, "Nonlinear fiber optics", 2nd edition, Academic Press, 1995, page 17).

Fig. 18 shows an optical communication line 23 according to the invention, comprising an optical cable including a 30   transmission fibre length 25 and a device 100 according to the invention.

The optical transmission fibre length 25 is a portion of optical fibre conventionally used for optical communications. Typically, it is a portion of single-mode

optical fibre at the wavelengths of interest.

The optical communication line 23 can be used either in a long distance transmission system or in distribution networks such as, for example, access networks.

5   According to the applications, the optical communication line 23 may also comprise an optical amplifier (not shown).

For example, the optical amplifier is of the conventional type and it comprises a portion of erbium-doped active optical fibre and a pump source (for example, a laser
10 source) for pumping the active optical fibre at a pumping wavelength. Typical example of pumping wavelengths for an erbium-doped active optical fibre are about 980 and 1480 nm.

Moreover, the optical amplifier can optionally comprise
15 more than one optical amplification stages.

According to an embodiment not shown, the optical communication line 23 of the invention comprises a plurality of optical transmission fibre lengths 25, a plurality of optical amplifiers interposed between a length
20 and the other of optical transmission fibre 25 and at least one wavelength converter device according to the invention (designed, for example, for compensating at least partly the chromatic dispersion of the plurality of optical transmission fibre lengths 25).

25 In general, the device of the invention can be arranged at the beginning, at the end or within the optical communication line 23. For example, in the case of application as spectral inverter, it can be inserted in the middle of the optical transmission fibre length 25 as
30 described by M.H. Chou ("*Efficient wide-band and tunable midspan spectral inverter using cascaded nonlinearities in LiNbO₃ waveguides*", IEEE Photonics Technology Letters, Vol. 12, No. 1, January 2000, pages 82-84).

Fig. 19 shows an optical communication system 21 according to the invention, comprising a transmitting station 22 for providing an optical signal radiation at a frequency ω_s, a receiving station 24 for receiving an optical signal

5   radiation, and an optical communication line 23 for transmitting the optical signal radiation.

According to a preferred embodiment, the optical communication system 21 is a WDM system.

In this case, the transmitting station 22 is a conventional

10 WDM equipment suitable to provide N optical signals having wavelengths $\lambda 1$, $\lambda 2$..... λN differing from one another (corresponding to frequencies ω_{s1}, ω_{s2}...ω_{sN}), to wavelength multiplex them and to send them in the optical communication line 23.

15 Preferably, the transmitting station 22 also comprises an optical power amplifier (booster, not shown) for amplifying the WDM optical signal before sending it along the line 23 (or a certain number of optical power amplifiers in parallel for amplifying optical signals comprised in

20 different wavelength bands).

Such wavelengths $\lambda 1$, $\lambda 2$..... λN are typically selected into a range of wavelengths comprised between about 1450nm and 1650nm.

Typically, the N optical signals are modulated signals, for

25 example at 100 Mbit/s, 1 Gbit/s, 2.5 Gbit/s, 10 Gbit/s, 20 Gbit/s, 40 Gbit/s or 80 Gbit/s. Furthermore, the N optical signals are typically frequency spaced by 12.5, 25, 50, 100 or 200 GHz.

The receiving station 24 comprises a conventional equipment

30 suitable to demultiplex a WDM optical signal at its input and to send the demultiplexed optical signals to optional further processing stages. Moreover, said receiving station 24 typically comprises also an optical pre-amplifier (not shown) suitable to bring the WDM optical signal at a

suitable power level to be received by the receiving equipment (or a certain number of optical pre-amplifiers in parallel for amplifying the optical signals comprised in different wavelength bands).

5   According to the applications, the line 23 may also comprise a plurality of conventional optical amplifiers (not shown) for amplifying a signal coming from an upstream portion of the line, in which the signal has attenuated during its propagation along it, and sending it in a

10   downstream portion of the line.

Alternatively, in place of each optical amplifier, the line 23 can comprise a number of optical amplifiers arranged in parallel for amplifying the optical signals comprised in different wavelength bands.

15   Fig. 20 shows an apparatus 26 for a WDM optical network node according to an embodiment of the invention, comprising a routing element 39, a plurality of wavelength converter devices 100 according to the invention, N input optical fibers 30, M output optical fibers 31, N

20   demultiplexing devices 27 and M multiplexing devices 28, with N, M $\geq$ 1 and N equal to or different from M.

In the embodiment shown, each input optical fiber 30 is optically connected to a respective 1xK1 demultiplexing device 27, the demultiplexing devices 27 are optically

25   connected to the input ports 32 of the routing element 39, each output port 33 of the routing element 39 is optically connected to a respective wavelength converter device 100, the outputs of the wavelength converter devices 100 are optically connected to M K2x1 multiplexing devices 28 and

30   each multiplexing device 28 is optically connected to a respective output optical fiber 31.

Each input optical fiber 30 carries K1 wavelength multiplexed optical signal radiation. The K1 wavelength multiplexed optical signal radiation are wavelength

demultiplexed by the demultiplexing devices 27 and sent to respective input ports 32. The optical signal radiation are then processed by the routing element 39, coupled to respective output ports 33, optionally wavelength converted
5   by the devices 100 and lastly wavelength multiplexed by the multiplexing devices 28 in M output multiplexed optical signal radiation. The M output multiplexed optical signal radiation are then sent to M respective output optical fibers 31.

10 The apparatus shown is capable of routing any input optical signal radiation to any output optical fiber 31 with any desired wavelength (comprised within the operating wavelengths of the devices 100), thanks to the wavelength converter devices 100.

15 In the embodiment shown, the routing element 39 has k1xN input ports 32 and k2xM output ports 33, with K1, K2 > 1 and K1 equal to or different from K2.

According to a variant, the demultiplexing devices 27 may have a number of output ports different from each other.
20 Furthermore, the multiplexing devices 28 may have a number of input ports different from each other.

The routing element may comprise a conventional optical switching matrix, a conventional add-drop device, a conventional cross-connect, a conventional λ-router or a
25 combination thereof.

The optical switching matrix may comprise MEMS (micro-electro-mechanical-systems), thermo-optical, electro-optical or magneto-optical switches which preferably are of the re-configurable type.

30 The apparatus 26 may be formed by integrated optics, fiber based or MEMS based technology.